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EXPLORATORY FLIGHT INVESTIGATION OF AIRCRAFT RESPONSE TO THE WING VORTEX WAKE GENERATED BY JET TRANSPORT AIRCRAFT

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16. Abstract

The effect of intercepting wing tip vortices generated by large jet transports, including jumbo jets, over separation distances from 1.85 kilometers (1 nautical mile) to 27.78 kilometers (15 nautical miles) is evaluated on the basis of the response of a vortex probe airplane in the roll mode. The vortex probe test aircraft included a representative general aviation airplane, an executive jet, a fighter, and light and mediumweight jet transports. The test conditions and airplane configurations were comparable to those normally used during takeoff, landing, or holding pattern operations. For flight safety the tests were performed at altitudes from 2896 meters (9500 feet) to 3810 meters (12,500 feet).

In addition to an evaluation of the probe airplane response, a flight test technique is suggested for determining minimum separation distance, using as variables the ratio of vortex-induced roll acceleration to maximum lateral control acceleration and the gross weight of the generating aircraft.

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INTRODUCTION

The wing trailing vortex system generated by an airplane has always been a potential hazard to aircraft penetrating the region of disturbance. The degree of the hazard depends primarily on the strength of the vortex system, the magnitude of the upset, and the recovery capability of the upset airplane. The strength of the vortex system is in turn dependent on airplane span loading and varies inversely with airspeed and air density. The recovery capability of the upset airplane depends on the control power available and the air space in which recovery can be made. Therefore, the greatest potential hazard for a small aircraft is in penetrating a vortex system generated by a large, heavily loaded aircraft that is traveling at low speeds and low altitudes.

The introduction of jet transports into airline service in 1959 increased the already present concern about the effect of successively larger aircraft on traffic spacing. With the advent of the jumbo jet which operates at approximately twice the gross weight of current jet transports, concern was again expressed over the possibility that the vortex wake shed by these aircraft would be a hazard to other aircraft flying within the terminal area. Consequently, the Federal Aviation Administration asked the National Aeronautics and Space Administration to conduct a flight program to evaluate the effect of the wing vortex wake of large jet transport airplanes on smaller following aircraft. The resulting flight test program was designed to obtain the data necessary to determine the location, apparent strength, and dissipation of the wing vortex behind large airplanes. The effects of wing vortex on the controlled response of several classes of aircraft, ranging from general aviation airplanes to mediumweight jet transports, at various separation distances were evaluated. The evaluations were based primarily on the probe aircraft's roll response at discrete separation distances behind the vortex generating airplane. For operational safety, tests were conducted at altitudes high enough to insure recovery from upsets.

This program was performed at Edwards Air Force Base under the supervision of the NASA Flight Research Center in cooperation with the U. S. Air Force C-5A Test Force and Space Positioning Branch, the Federal Aviation Administration, and the NASA Ames Research Center.

This paper summarizes the results of the test program and suggests a means by which the data may be used as a guideline to rational aircraft separations in the air traffic system.

SYMBOLS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U. S. Customary Units. The measurements were taken in U. S. Customary Units. Factors relating the two systems are presented in NASA SP-7012, "The International System of Units - Physical Constants and Conversion Factors" by E. A. Mechtly.

a_n	normal acceleration, g
a_y	lateral acceleration, g
p	roll rate, deg/sec
$\dot{p}$	roll acceleration, rad/sec^2
$\lvert\dot{p}\rvert_{measured}$	absolute maximum roll acceleration measured during vortex penetration, rad/sec^2
$\lvert\dot{p}\rvert_{\delta_{max}}$	absolute roll acceleration produced by maximum lateral control deflection, rad/sec^2
q	pitch rate, deg/sec
r	yaw rate, deg/sec
t	time, sec
α	angle of attack, deg
β	angle of sideslip, deg
δ	aileron deflection, deg
δ_t	total aileron deflection, trailing edge up negative, $(\delta_{left} - \delta_{right})$, deg
Θ	pitch angle, deg
φ	roll angle, deg
φ_w	lateral control wheel deflection, deg
$\Delta\varphi$	incremental roll angle, deg

TEST AIRPLANES AND TEST CONDITIONS

Table 1 lists the airplanes used in the program together with the flight conditions and the separation distances investigated. Initially, a Boeing B-52 and a Lockheed

C-5A were used as vortex generating airplanes and were flown in both the clean configuration and in several landing flap configurations at indicated airspeeds of 135 knots to 220 knots. A Lockheed F-104 and a Convair 990 were used to probe the vortex wake of these aircraft at separation distances from 1.85 kilometers (1 nautical mile) to 27.78 kilometers (15 nautical miles). A test altitude of 3810 meters (12,500 feet) was selected.

Following a preliminary analysis of these flight test results, a second series of tests was conducted in which the vortex generating aircraft were the C-5A, Convair 990, and a McDonnell Douglas DC-9. The probe airplanes for this test series were the Convair 990, DC-9, Learjet 23, and a Cessna 210. All tests were performed again at an altitude of 3810 meters (12,500 feet), except for the tests with the Cessna 210, which were conducted at 2896 meters (9500 feet). The generating airplanes were flown in both the clean and the landing flap configuration. However, for flight safety, the Learjet 23 and Cessna 210 did not probe the vortex wake of the C-5A in the clean configuration. Indicated airspeeds for this test series ranged from 130 knots to 200 knots.

TEST PROCEDURES

During the first test series, the probe airplane was positioned in the right-hand vortex and the pilot was requested to position and maintain the airplane in the wake from the farthest point of vortex detection to a specified minimum separation distance. The pilot was further instructed to return the airplane to the wake path as soon as possible after an upset generated by the wake. Conducting the test in this manner provided a means for assessing the wake dissipation, the apparent wake strength, the associated airplane upset tendency, and the vertical location of the wake relative to the generating airplane.

A racetrack pattern approximately 185 kilometers (100 nautical miles) long was established at the assigned altitude. The normal engine exhaust smoke of the B-52 and the C-5A was used to identify the location of the vortex trail. The wake from the C-5A was detectable from distances up to 37 kilometers (20 nautical miles), depending on atmospheric conditions. From 1.85 kilometers (1 nautical mile) to 7.41 kilometers (4 nautical miles), the smoke trail was well defined; however, the region of highest wake intensity was not located easily. The smoke trail from the B-52 was of a somewhat lower density than that from the C-5A and was not detectable beyond 9.26 kilometers (5 nautical miles). During these tests, the lateral and vertical separation of the probe and the generating aircraft were measured by the Air Force Space Positioning Branch. FPS-16 and Nike Ajax radars were used, and several of the tests were observed and recorded on a video tape system.

During the second test series, the probe aircraft was positioned by radar a specified distance behind the generating aircraft. From this point the probe aircraft flew in the wake for 2 minutes to 3 minutes to record sufficient airplane response data. The generating aircraft was usually evaluated in both the landing flap and the clean configuration and at airspeeds consistent with standard operating procedures in the terminal area of the flight envelope. In two of the test sequences the C-5A and the Convair 990 were flown in formation on a parallel course, and the probe aircraft intersected the wakes of the two airplanes alternately. The Convair 990 and the DC-9 were also flown in formation, and the probe aircraft also intersected their wakes.

As noted previously, smoke from the engines of the generating aircraft was used to mark the wake trail. This method was satisfactory with the C-5A airplane; however, to increase the density of the smoke generated by the Convair 990 and the DC-9, thereby improving the marking of the vortex wake, JP-5 fuel was burned in the engines during the tests. The DC-9 still lacked adequate smoke to mark the wake; consequently, the data for the probe aircraft in the wake of the DC-9 are limited.

INSTRUMENTATION

A portable data acquisition package was used to record airplane responses during tests conducted with the Convair 990 and the DC-9 as the probe aircraft. Parameters recorded included:

Airspeed

Altitude

Normal acceleration

Longitudinal acceleration

Transverse acceleration

Pitch velocity

Roll velocity

Yaw velocity

Bank angle

Angle of attack (Convair 990)

Angle of sideslip (Convair 990)

Lateral control wheel position

The data were recorded on a 14-track Parsons FM tape recorder installed in the package.

Airplane response data from the F-104 airplane were similar to those recorded in the other airplanes; however, these data were telemetered to a ground station and displayed in real time.

The Learjet 23 and Cessna 210 aircraft were instrumented with comparable data acquisition and recording systems installed by Ames Research Center and FAA personnel, respectively. The instrumentation systems recorded airspeed and altitude as well as standard handling-qualities parameters.

The accuracy and range of all recorded parameters were within limits normally

accepted in handling-qualities analysis, and time between the airborne and radar space-positioning data was correlated through a common timing system.

ANALYSIS OF FLIGHT RESULTS

Vortex Wake Location

The vertical location of the vortex wake generated by the C-5A in the clean configuration at an indicated airspeed of 170 knots and an altitude of 3810 meters (12,500 feet) is presented in figure 1(a). The right-hand vortex wake of the C-5A was first intercepted by the Convair 990 airplane at 20.33 kilometers (11 nautical miles). Recorded data and crew comments indicate that the airplane remained in the wake up to a separation distance of 5.56 kilometers (3 nautical miles). The C-5A was under autopilot control to maintain constant altitude, and vertical separation between the two aircraft was determined from one-sample-per-second FPS-16 radar data. These data show that the vertical displacement of the vortex wake about the average downward path was somewhat random, varying between 30.5 meters (100 feet) and 61.0 meters (200 feet).

During the various test runs, it was noted that the smoke trail that identified the vortex wake path of the generating airplane appeared to vary sinuously. The smoke usually descended below the generating airplane; however, on several occasions the smoke tended to return toward the prescribed cruise altitude of the generating airplane. This tendency may have been the result of atmospheric buoyancy; however, a much more detailed investigation would be necessary for direct correlation. Lateral displacements of the probe airplane relative to the generating airplane, caused by crosswinds at the test altitude, were also noted in the radar tracking data. Thus, it is mandatory that the vortex trail be marked in order to assess wake behavior, particularly at extreme separation ranges.

Figure 1(b) summarizes the average vertical vortex location as a function of aircraft separation range, taken from data recorded during several tests with the C-5A as the generating airplane. The average vortex location in this series of tests varied from 229 meters (750 feet) to 305 meters (1000 feet) below the generating airplane at separation distances of 16.67 kilometers (9 nautical miles) to 20.37 kilometers (11 nautical miles).

To obtain additional information, an F-104 was used to mark the vertical vortex path of the C-5A during cruise at a Mach number of approximately 0.8 and an altitude of 11,278 meters (37,000 feet). The vortex path was identified by condensation trails. At a distance of 5.56 kilometers (3 nautical miles) behind the C-5A, the wake had descended to 11,125 meters (36,500 feet). It remained at this altitude for more than 74.1 kilometers (40 nautical miles).

Airplane Response to Vortices

To simplify the following data presentation, nominal flight conditions for data

presented in figures 2 to 5 are listed in table 2.

Figure 2 presents representative time histories of various probe airplane responses to vortices generated behind the C-5A and Convair 990 aircraft. In the analysis of these data it was assumed that the probe airplane had encountered a region of vortex flow when the airplane's angular acceleration in roll was definitely in opposition to lateral control inputs. Further, when the probe aircraft's instrumentation included a sideslip vane, transient response of this vane independent of airplane motion served as an additional indicator of an encounter with the vortex path.

Figure 2(a) shows the response of the F-104 while flying behind a C-5A in the clean configuration. The vortex penetration of the F-104 was performed at a true airspeed of about 360 knots. The vortex was intersected at 3 seconds when the separation distance between the two aircraft was 16.5 kilometers (8.9 nautical miles). On several of the vortex penetrations of this type, the F-104 experienced altitude losses of 305 meters (1000 feet) to 457 meters (1500 feet) during the recovery from the upset.

Figure 2(b) shows a vortex wake encounter with the Learjet 23 following the C-5A configured for the landing approach. Separation distance between the two aircraft was 6.85 kilometers (3.7 nautical miles). Despite opposing lateral control inputs, the Learjet was inverted within about 2 seconds. Vortex intersection, evidenced first by sideslip vane response and secondly by increased roll acceleration, took place between 2 seconds and 2.5 seconds.

Figure 2(c) illustrates the response of the Cessna 210 to the wake of the Convair 990 flying with landing approach flaps extended. The aircraft were 5.18 kilometers (2.8 nautical miles) apart. On the basis of roll acceleration and the abrupt change in bank angle, it was determined that vortex intersection occurred at $t = 0.75$ second.

Shown in figure 2(d) is the response of the DC-9 following the C-5A in the clean configuration at a distance of 8.7 kilometers (4.7 nautical miles). Vortex intersection occurred at 6 seconds, as shown primarily by the roll acceleration, the abrupt change in bank angle, and the lateral control input. Flow direction vanes were not installed on the DC-9.

Figure 2(e) shows the response of the Convair 990, the largest probe aircraft flown during this program, to a C-5A wake. Both aircraft were in the landing approach configuration and were separated by 5.37 kilometers (2.9 nautical miles). From the sideslip vane response, it appears that the vortex interception occurred at $t = 7$ seconds. The probe aircraft rolled almost 40° with full lateral control applied to oppose the roll.

A general observation from these time histories is that all the probe aircraft experienced appreciable disturbances of the Dutch roll mode as well as the roll mode. This is shown in the yawing excursions which accompanied the predominant rolling excursions. Although no attempt is made to account for this Dutch-roll excitation, these excursions may present an additional structural or controllability hazard and should be considered in future flight studies.

Maximum Excursions from Vortices

Maximum responses of five probe airplanes to the C-5A vortex wake are summarized in figure 3 as a function of aircraft spacing. The parameters used for this summary are excursions in normal acceleration, transverse acceleration, roll rate, and the lateral control input during each encounter with the C-5A wake.

Figure 3(a) summarizes the F-104 responses to the C-5A airplane in the clean and landing configurations. Excursions in normal acceleration and roll rate do not indicate any apparent attenuation over the range of separation distances tested. The large excursions in roll rate are somewhat indicative of the characteristic responses of the F-104 airplane. The airplane is easily disturbed in roll and can attain rather large roll rates, 170 degrees per second in this instance. This is attributed primarily to low roll inertia and damping of the aircraft in conjunction with pilot reaction time and limits in lateral control reaction effectiveness. At small separation distances, the apparent reduction in maximum roll rate is considered to be the result of a poor definition of the vortex core location, not a reduction in the vortex strength.

Figure 3(b) summarizes the Convair 990 response to the C-5A in the clean and landing configurations. The normal acceleration excursions vary from 0g to 1.3g at 6.48 kilometers (3.5 nautical miles) to 0.5g and 1.1g at 23.2 kilometers (12.5 nautical miles). There is some apparent reduction in the normal acceleration excursions with increased separation distance. Transverse acceleration varies from about 0.2g to 0.03g and roll rates vary from approximately 15 degrees per second to 5 degrees per second over most of the separation range tested. The roll rate excursions and the lateral control activity indicate some attenuation beyond 18.5 kilometers (10 nautical miles), and little vortex activity could be detected beyond this point. Also, lateral control activity is reduced from near full deflection with the generating aircraft in the clean configuration to less than one-half deflection with the generating aircraft in the landing configurations in the 12.96-kilometer (7-nautical-mile) to 18.52-kilometer (10-nautical-mile) separation range.

Figures 3(c) to 3(e) summarize the response of the DC-9, the Learjet 23, and the Cessna 210 to the wing vortex wake of the C-5A.

Although no definitive statement regarding wake attenuation can be made, the data suggest that significant vorticity persisted as far as 18.52 kilometers (10 nautical miles) behind the C-5A in the clean configuration. When the landing flaps were lowered, however, vortex-induced disturbances were largely attenuated at a separation range of 14.82 kilometers (8 nautical miles).

Pilot Effort

To further illustrate the attenuation of vortex wake intensity that accompanies increasing separation distance and change in the configuration of the generating airplane, figure 4 summarizes pilot activity while flying in the wing-tip vortex system for 30 seconds at discrete separation ranges. Data are presented for the Convair 990 probing the wake of the C-5A in the clean and the landing approach configurations. The data illustrate the percentage of a 30-second sample period that one-third, two-thirds, and full lateral wheel deflection were used to maintain the airplane within the vortex wake boundary. It is evident from the clean-configuration data (fig. 4(a)) that the predominant control input is to the right to counteract the counterclockwise moment

produced by the vortex. Up to the 16.67-kilometer (9-nautical-mile) separation distance, at least one-third wheel deflection was required 50 percent of the time. Also, within this separation range, full-wheel deflection was required approximately 10 percent of the time to prevent ejection from the wake path. Beyond the 16.67-kilometer (9-nautical-mile) separation distance, the control manipulation required is considerably reduced, either because of a reduced vortex core definition or reduced vortex strength. For the C-5A in the landing configuration (fig. 4(b)), the lateral control input required decreases over the entire range of test conditions, with a marked decrease in the range of 11.11 kilometers (6 nautical miles) to 16.67 kilometers (9 nautical miles). The previously discussed attenuation of the vortex influence due to landing-flap deployment is illustrated by these data. In this instance, the separation distance where one-third wheel deflection exceeds 50 percent of the sample time is 7.41 kilometers (4 nautical miles).

Roll Response Summary

Figure 5 summarizes the roll response characteristics of the various probe and generating aircraft combinations tested in the landing flap configuration. Maximum bank angle and roll velocities experienced as a function of separation distance are presented. These data were measured primarily during the initial period of probe airplane upset when the pilot was applying lateral control to oppose the vortex-induced rolling moment.

Figure 5(a) presents the DC-9 response data resulting from an intersection of the vortex wake of the Convair 990 and C-5A generating aircraft between separation distances of 4.63 kilometers (2.5 nautical miles) to 18.52 kilometers (10 nautical miles). The indicated airspeed of both the probe and generating aircraft was approximately 150 knots. As a general observation, the DC-9 response to the wake of the C-5A is considerably greater than that experienced behind the Convair 990. For example, at a separation distance of 9.8 kilometers (5.5 nautical miles) the maximum bank angle and roll response behind the C-5A is on the order of 48° and 38 degrees per second, respectively. The maximum bank angle and roll rate response to the Convair 990 at a corresponding separation range was essentially 18° and 15 degrees per second. The test behind the C-5A was terminated at a distance of 6.85 kilometers (3.7 nautical miles) because of the pilot's concern for the safety of the aircraft.

Figure 5(b) summarizes the Cessna 210 roll response to the Convair 990, C-5A, and DC-9 generating aircraft over a separation distance of 4.63 kilometers (2.5 nautical miles) to 16.11 kilometers (8.7 nautical miles). In this series of tests, the indicated airspeed of the Cessna 210 was maintained at 130 knots; the indicated airspeeds of the generating aircraft were maintained at 130 knots to 140 knots. Again, the influence of the C-5A is readily apparent from the large bank angles experienced, particularly from 7.41 kilometers (4 nautical miles) to 9.26 kilometers (5 nautical miles). These data were obtained from pilot notes, because the on-board data acquisition system in the Cessna 210 was damaged by the violent maneuvering experienced by the airplane during the final tests. In this separation range the response to the Convair 990 wake was considerably reduced. However, between 4.63 kilometers (2.5 nautical miles) and 7.41 kilometers (4 nautical miles) it was obvious from the increased severity of the airplane upsets that the intensity of the wake increased significantly. For example, at 7.41 kilometers (4 nautical miles) the maximum indicated bank angle was approximately 45° while the corresponding roll velocity was about 60 degrees per second.

As mentioned previously, response to the DC-9 vorticity was limited to some degree by the inability to detect the wake much beyond 9.26 kilometers (5 nautical miles). The limited data obtained, however, showed that roll response of the probe airplane to the DC-9 wake was less than that resulting from either the Convair 990 or C-5A airplane.

Figure 5(c) presents the Learjet 23 roll response to the Convair 990, DC-9, and C-5A aircraft. The generating aircraft indicated airspeeds were approximately 145 knots. A comparison of the Learjet response to the wake of the Convair 990 and C-5A shows the increased strength of the wake generated by the C-5A airplane. For example, with a separation distance of approximately 9.26 kilometers (5 nautical miles), the response to the Convair 990 wake vortex in terms of maximum bank angle and roll velocity is approximately 40° and 30 degrees per second, respectively. In the vortex of the C-5A, bank angles are on the order of 120° in conjunction with a rolling velocity of approximately 55 degrees per second. The limited data obtained when the Learjet 23 probed the vortex of the DC-9 appear to be consistent with the general trend.

In general, the roll response summary data substantiate the belief that wake strength increases in proportion to generating aircraft size and weight. In all the cases tested, at comparable separation distance, probe aircraft response increased as the wake penetration testing progressed from the DC-9 to the Convair 990 and finally to the C-5A airplane.

Minimum Separation Distance

The data presented have shown the response of the probe aircraft to the wing vortices of the generating aircraft. The application of this information to the determination of minimum aircraft separation distance is presented in figures 6 to 8. A flight test demonstration technique which may be used, in conjunction with pilot opinion, to establish baseline separation standards for out-of-ground-effect flight conditions was developed. Once the baseline is established with this technique, other factors can be introduced to account for additional variables, such as wind and temperature gradients, and ground effect, which would be present in the final phase of terminal-area flight operations. Minimum separation distance may be determined exclusively from these flight tests, using as parameters the ratio of vortex-induced roll acceleration measured by the probe aircraft to maximum lateral control roll acceleration of the probe aircraft and gross weight of the generating aircraft.

Figure 6 is a summary of typical data derived from this technique with the Convair 990, DC-9, and Learjet 23 in the wake of the C-5A in the landing configuration at an indicated airspeed of 150 knots. The ratio of the maximum measured roll acceleration produced by the wake of the generating airplane to the maximum available roll control power of the probe airplane is plotted as a function of separation distance. When the maximum control power of the probe airplane was equal to the rolling acceleration produced by the wake of the generating airplane, the separation distance between the aircraft was assumed to be a safe minimum. Data obtained from test runs of the various airplane combinations were plotted and a line was drawn representing the maximum boundary of the data. The point where the boundary line intersected the value of 1 was considered to be the safe separation distance of the aircraft combination tested. For example, the minimum safe distance behind the C-5A would be 14.45 kilometers (7.8 nautical miles) for the Learjet 23, 12 kilometers (6.5 nautical miles) for the DC-9, and 10 kilometers (5.2 nautical miles) for the Convair 990.

Figure 7 presents similar data for the Learjet 23 and DC-9 operating behind the Convair 990. The Convair 990 was in the landing configuration and flying at an indicated airspeed of 150 knots. Using the same criteria as for figure 6, the Learjet 23 minimum separation distance should be approximately 8 kilometers (4.3 nautical miles) and the DC-9 separation distance should be about 4.26 kilometers (2.3 nautical miles). For the test conditions of figures 6 and 7, maximum control power parameters, $|\dot{p}|_{\delta_{max}}$, for the Learjet 23, Convair 990, and DC-9 were 95, 14, and 40 degrees per second^2, respectively.

Figure 8 summarizes the minimum spacing as a function of the average gross weight of the generating airplane. The data were derived from the information in figures 6 and 7 and are compared with pilot estimates of the minimum separation distance during the tests. Pilot opinion was based on the ability to maintain the airplane in the vortex and within a limited bank angle or roll rate limit. For general aviation aircraft these limits were approximately ±30° in bank angle or 45 degrees per second in roll rate. The limits were reduced to approximately ±15° and 30 degrees per second for airplanes in the general transport class. In the pilot assessment, consideration was also given to the normal operation of the airplane being tested and to the average crew and passenger response to a similar disturbance.

In the gross weight range of 204,082 kilograms (450,000 pounds) to 272,109 kilograms (600,000 pounds), represented by the C-5A, there was general agreement between the measured data and pilot opinion. For the Convair 990 and DC-9 probe airplanes, it appears that the pilot would tolerate, respectively, a 2.78-kilometer (1.5-nautical-mile) and 0.93-kilometer (0.5-nautical-mile) reduction in the separation below that specified by the measured data. However, for the Learjet 23 probe aircraft the agreement was good, and, if anything, pilot opinion would indicate a slightly greater spacing requirement. For an average generating aircraft gross weight of 90,720 kilograms (200,000 pounds), represented by the Convair 990, the agreement between the measured data and pilot opinion was good. There appears to be a deviation of only 0.93 kilometer (0.5 nautical mile) to 1.39 kilometers (0.75 nautical mile) in the minimum aircraft separation distance.

To implement the technique, a series of preliminary tests would have to be performed to determine the lateral control power of the prospective probe airplane. This phase would be followed by a series of systematic test runs of the probe airplane behind generating airplanes of various gross weights. As an example, figure 2 presents typical time histories of the type of data necessary to determine the numerator term of the acceleration ratio. Maximum acceleration would be measured either directly or from the slope of the roll rate data at the point of large transient response in sideslip indication, change in bank angle, or opposing lateral control inputs.

CONCLUDING REMARKS

A flight study was conducted to observe the behavior of the wing tip vortex generated by large transport airplanes over separation ranges as great as 27.78 kilometers (15 nautical miles) and to evaluate the controllability of airplanes intercepting this vortex trail. From these studies it was found that the wake intensity, or strength, was influenced by the weight and configuration of the generating aircraft. The strongest wake was generated by a C-5A airplane in the clean configuration; at comparable speed

and altitude there was a measurable reduction in wake strength when the C-5A was in the landing configuration.

Radar space-positioning data indicated that in a holding pattern or at landing-approach speeds of approximately 170 knots, the average vertical downwash of the vortex varied from 229 meters (750 feet) to 305 meters (1000 feet) below the generating airplane at a separation distance of 16.67 kilometers (9 nautical miles) to 20.37 kilometers (11 nautical miles). Atmospheric conditions can produce random vertical oscillations of from 30.5 meters (100 feet) to 61.0 meters (200 feet) about the radar defined downwash path.

Test results indicated that aircraft with a short wing span can sustain uncontrollable upsets from a desired flight path when they intercept the wing vortex wake of a heavy or jumbo jet aircraft within 14.9 kilometers (8 nautical miles) separation distance.

All the probe aircraft experienced appreciable disturbances of the Dutch roll mode, as well as the roll mode.

A method suggested for establishing minimum separation distances between aircraft in out-of-ground-effect flight conditions could be used, in conjunction with pilot opinion, to provide baseline data for determining minimum separation distances for a large variety of airplanes operating within the air traffic system.

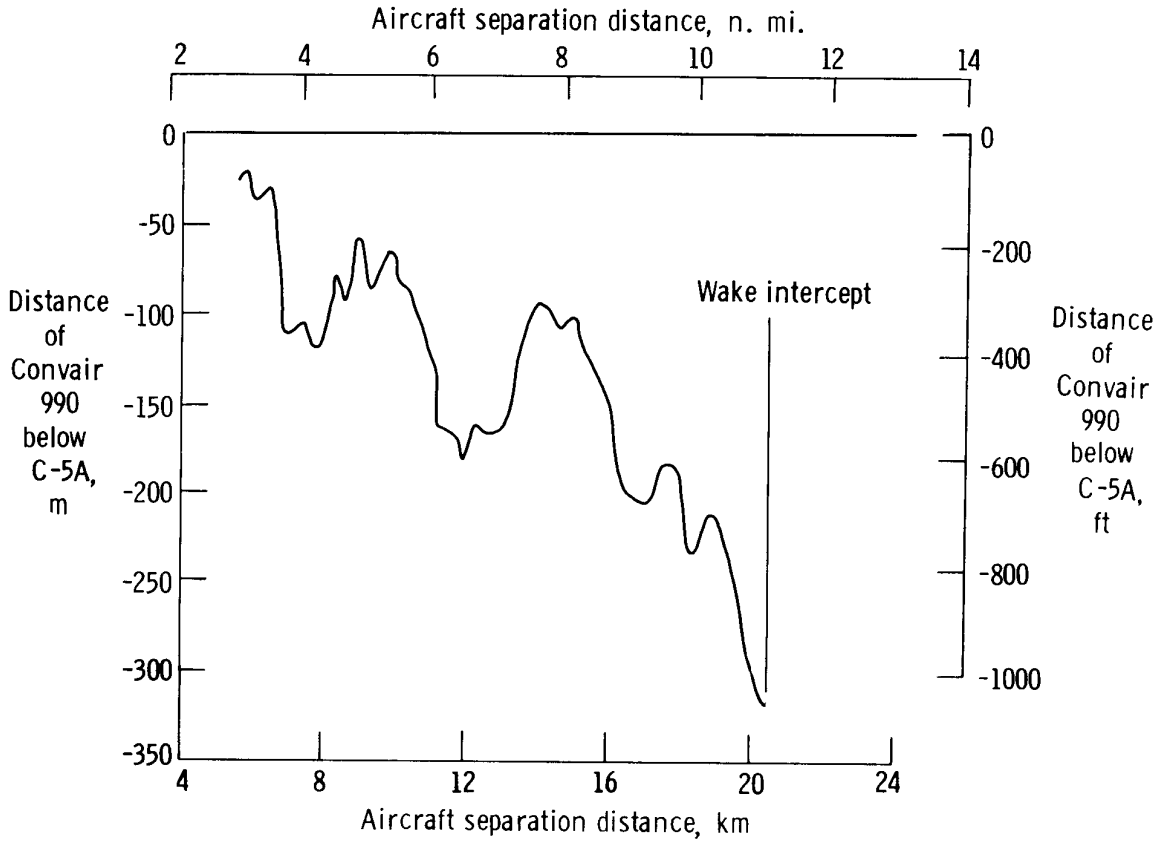
Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., October 29, 1971.

TABLE 1. - SUMMARY OF AIRCRAFT AND FLIGHT CONDITIONS INVESTIGATED DURING WING VORTEX STUDY

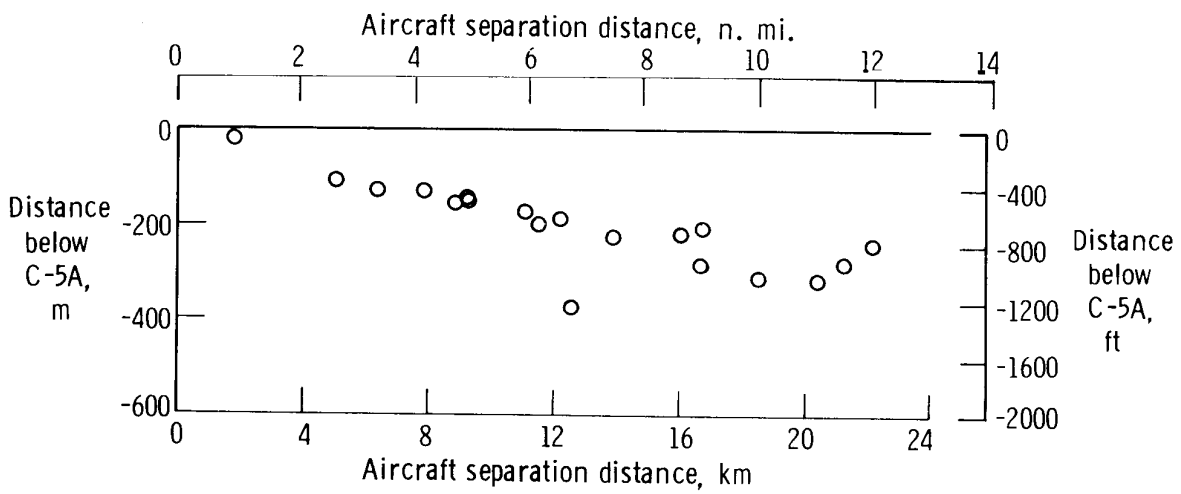
Probe aircraft	Generating aircraft				Separation distance, km (n. mi.)	Test altitude, m (ft)
	Type	Indicated airspeed, knots	Gross weight, kg (lb)	Configuration		
F-104	B-52	170 to 220	106.6 to 114.3 × 10^3 (235 to 252 × 10^3)	Clean	1.85 to 18.52 (1 to 10)	3810 (12,500)
F-104	C-5A	135 to 170	199.6 to 267.6 × 10^3 (440 to 590 × 10^3)	Clean, landing flap	1.85 to 27.78 (1 to 15)	3810 (12,500)
Convair 990	C-5A	135 to 190	212.3 to 279.0 (468 to 615)	Clean, landing flap	5.37 to 27.78 (2.9 to 15)	3810 (12,500)
DC-9	C-5A	150 to 190	263.1 to 277.6 (580 to 612)	Clean, landing flap	6.85 to 18.52 (3.7 to 10)	3810 (12,500)
Learjet 23	C-5A	140	202.3 to 207.3 (446 to 457)	Landing flap	6.48 to 18.52 (3.5 to 10)	3810 (12,500)
Cessna 210	C-5A	130 to 140	244.5 to 249.9 (539 to 551)	Landing flap	6.48 to 18.52 (3.5 to 10)	2896 (9500)
DC-9	Convair 990	145 to 180	69.4 to 93.4 × 10^3 (153 to 206 × 10^3)	Clean, landing flap	4.63 to 16.67 (2.5 to 9)	3810 (12,500)
Learjet 23	Convair 990	150 to 200	88.4 to 93.4 (195 to 206)	Clean, landing flap	6.48 to 12.96 (3.5 to 7)	3810 (12,500)
Cessna 210	Convair 990	130	70.3 to 77.6 (155 to 171)	Clean, landing flap	3.70 to 13.89 (2 to 7.5)	2896 (9500)
Learjet 23	DC-9	150 to 170	31.3 to 33.1 × 10^3 (69 to 73 × 10^3)	Clean, landing flap	5.56 to 9.26 (3 to 5)	3810 (12,500)
Cessna 210	DC-9	130	29.0 to 31.3 (64 to 69)	Clean, landing flap	5.56 to 9.26 (3 to 5)	2896 (9500)

TABLE 2. - SUMMARY OF AIRCRAFT AND FLIGHT CONDITIONS FOR FIGURES 2 TO 5

Generating aircraft					Probe aircraft				
Figure	Aircraft	Configuration	Gross weight, kg (lb)	Indicated airspeed, knots	Aircraft	Configuration	Gross weight, kg (lb)	Indicated airspeed, knots	Test altitude, km (ft)
2(a)	C-5A	Clean	265,350 (585,000)	170	F-104	Clean	7260 (16,000)	300	3810 (12,500)
2(b)	C-5A	25° flap (landing approach)	202,980 (447,500)	140	Learjet 23	20° flap	5220 (11,500)	140	3810 (12,500)
2(c)	Convair 990	27° flap (landing approach)	76,200 (168,000)	130	Cessna 210	Clean	1360 (3000)	130	2896 (9500)
2(d)	C-5A	Clean	274,880 (606,000)	190	DC-9	Clean	31,520 (69,500)	190	3810 (12,500)
2(e)	C-5A	25° flap	271,480 (598,500)	150	Convair 990	27° flap	73,260 (161,500)	150	3810 (12,500)
3(a)	C-5A	Clean	207,290 to 267,620 (457 to 590,000)	170	F-104	Clean	7260 to 8160 (16 to 18,000)	250 to 300	3810 (12,500)
		40° flap (landing)	205,020 (452,000)	165	F-104	Clean	7710 (17,000)	260	3810 (12,500)
3(b)	C-5A	Clean	225,890 (498,000)	170	Convair 990	Clean	80,280 (177,000)	250	3810 (12,500)
		40° flap	220,000 (485,000)	165	Convair 990	Clean	78,920 (174,000)	250	3810 (12,500)
		25° flap	213,640 (471,000)	135	Convair 990	36° flap	74,390 (164,000)	200	3810 (12,500)
3(c)	C-5A	Clean	276,240 (609,000)	190	DC-9	Clean	30,570 (67,400)	190	3810 (12,500)
		40° flap	269,890 (595,000)	150	DC-9	30° flap (gear down)	29,760 (65,600)	150	3810 (12,500)
3(d)	C-5A	25° flap	204,120 (450,000)	140	Learjet 23	20° flap	5220 (11,500)	140	3810 (12,500)
3(e)	C-5A	25° flap	249,480 (550,000)	135	Cessna 210	Clean	1360 (3000)	130	2896 (9500)
4	C-5A	Clean	225,440 (497,000)	170	Convair 990	Clean	80,740 (178,000)	250	3810 (12,500)
	C-5A	40° flap	220,000 (485,000)	165	Convair 990	Clean	78,920 (174,000)	200	3810 (12,500)
5(a)	Convair 990	36° flap (landing)	72,570 to 90,490 (160 to 199,500)	150	DC-9	30° to 50° flap (gear down)	30,390 to 31,980 (67 to 70,500)	150	3810 (12,500)
	C-5A	40° flap	270,340 to 273,970 (596 to 604,000)	150	DC-9	30° to 50° flap (gear down)	30,390 to 31,980 (67 to 70,500)	150	3810 (12,500)
5(b)	Convair 990	27° flap	71,210 to 78,020 (157 to 172,000)	130	Cessna 210	Clean	1360 (3000)	130	2896 (9500)
	DC-9	50° flap (gear down)	29,940 to 31,300 (66 to 69,000)	130	Cessna 210	Clean	1360 (3000)	130	2896 (9500)
	C-5A	25° flap	248,570 to 250,380 (548 to 552,000)	130 to 140	Cessna 210	Clean	1360 (3000)	130	2896 (9500)
5(c)	C-5A	25° flap	202,760 to 207,300 (447 to 457,000)	140	Learjet 23	20° flap	5220 (11,500)	140	3810 (12,500)
	Convair 990	36° flap	88,450 to 90,490 (195 to 199,500)	150	Learjet 23	20° flap	5220 (11,500)	150	3810 (12,500)
	DC-9	50° flap (gear down)	31,520 (69,500)	150	Learjet 23	20° flap	5220 (11,500)	150	3810 (12,500)

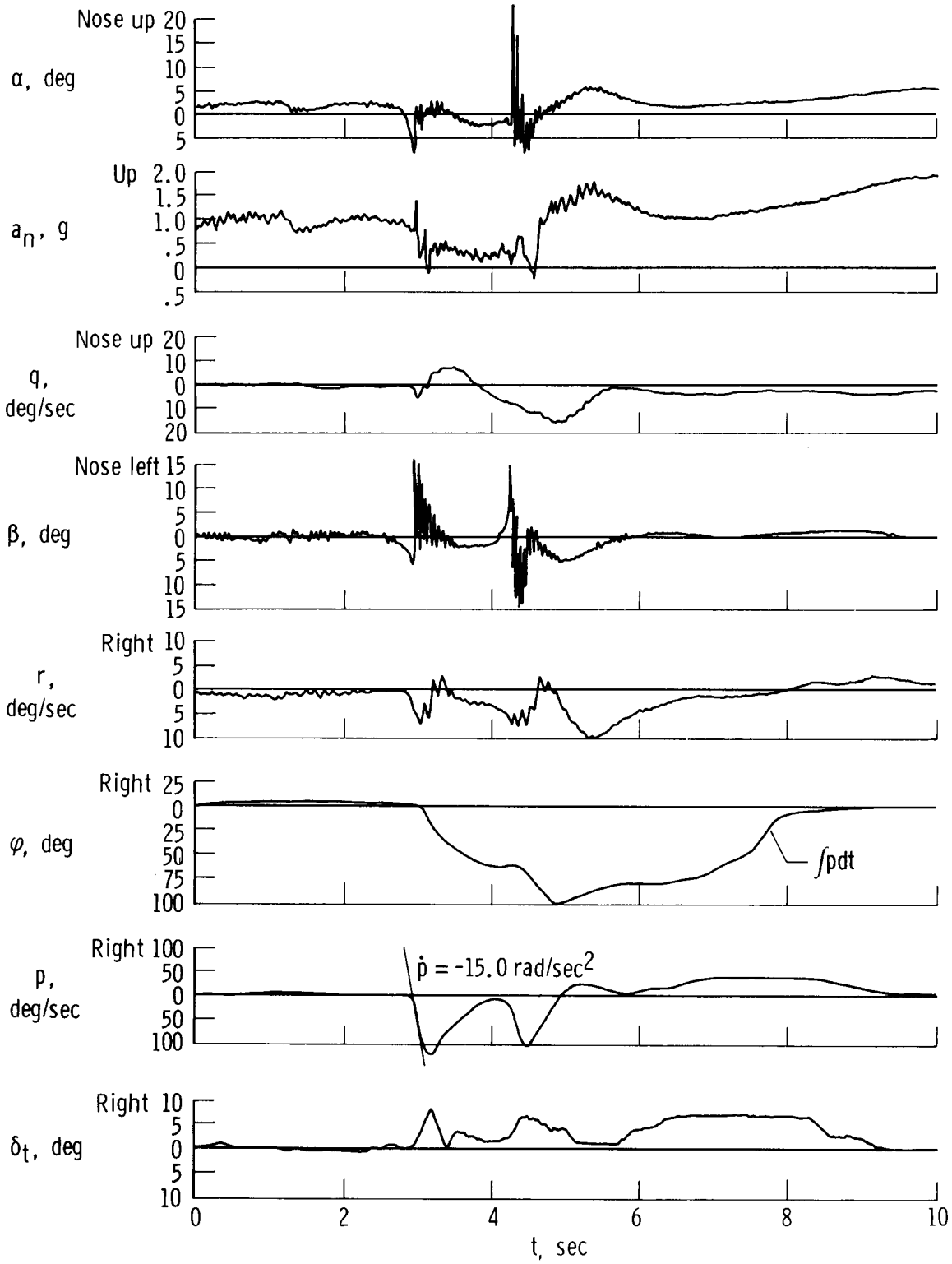


(a) Typical altitude variation of the Convair 990 flying in the wing vortex wake of the C-5A in the clean configuration. C-5A indicated airspeed, 170 knots; altitude, 3810 m (12,500 ft).



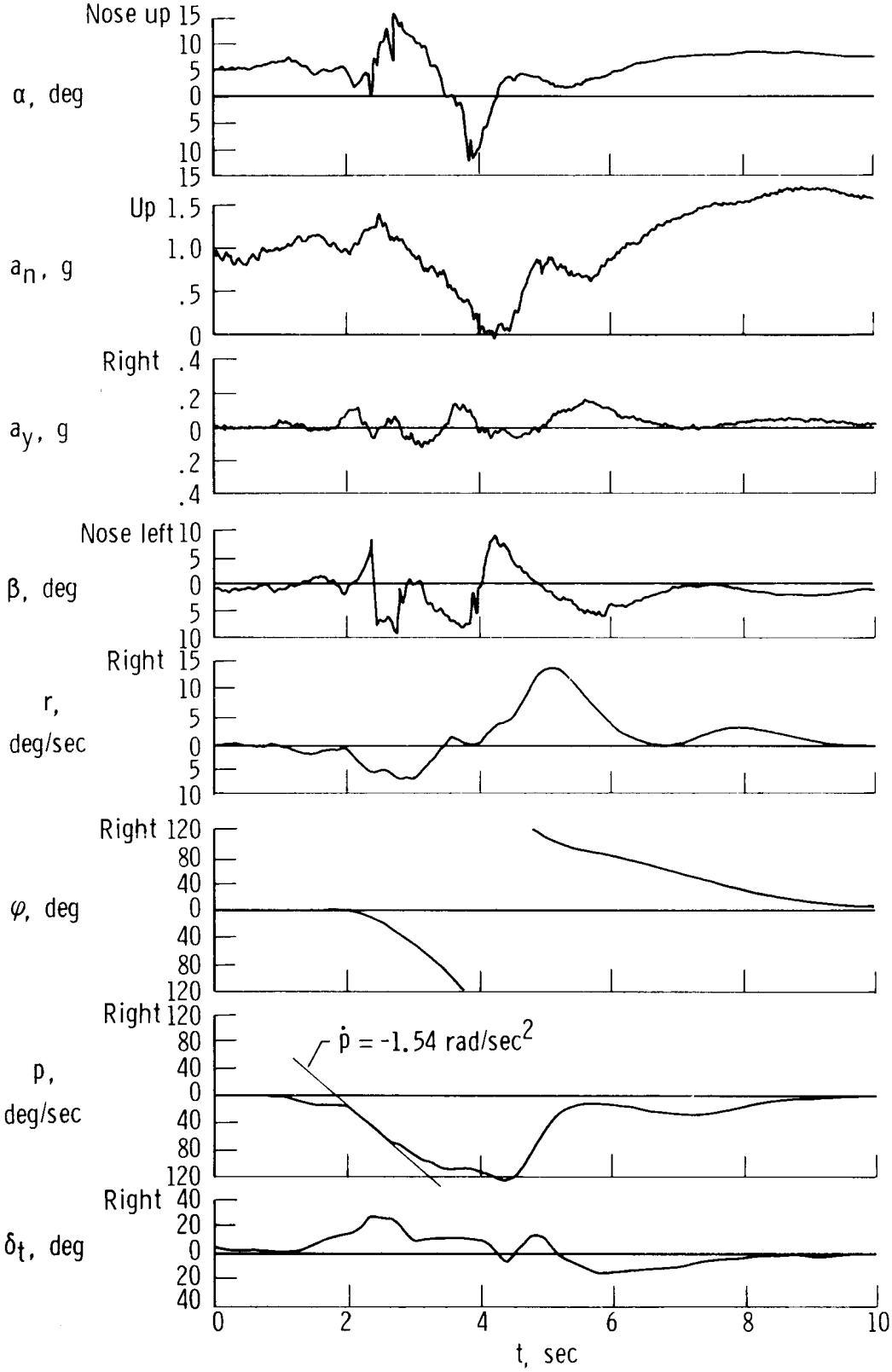
(b) Average vertical wing vortex location behind the C-5A generating airplane.

Figure 1. Vertical location of the wing vortex wake generated by the C-5A airplane. FPS-16 radar data.



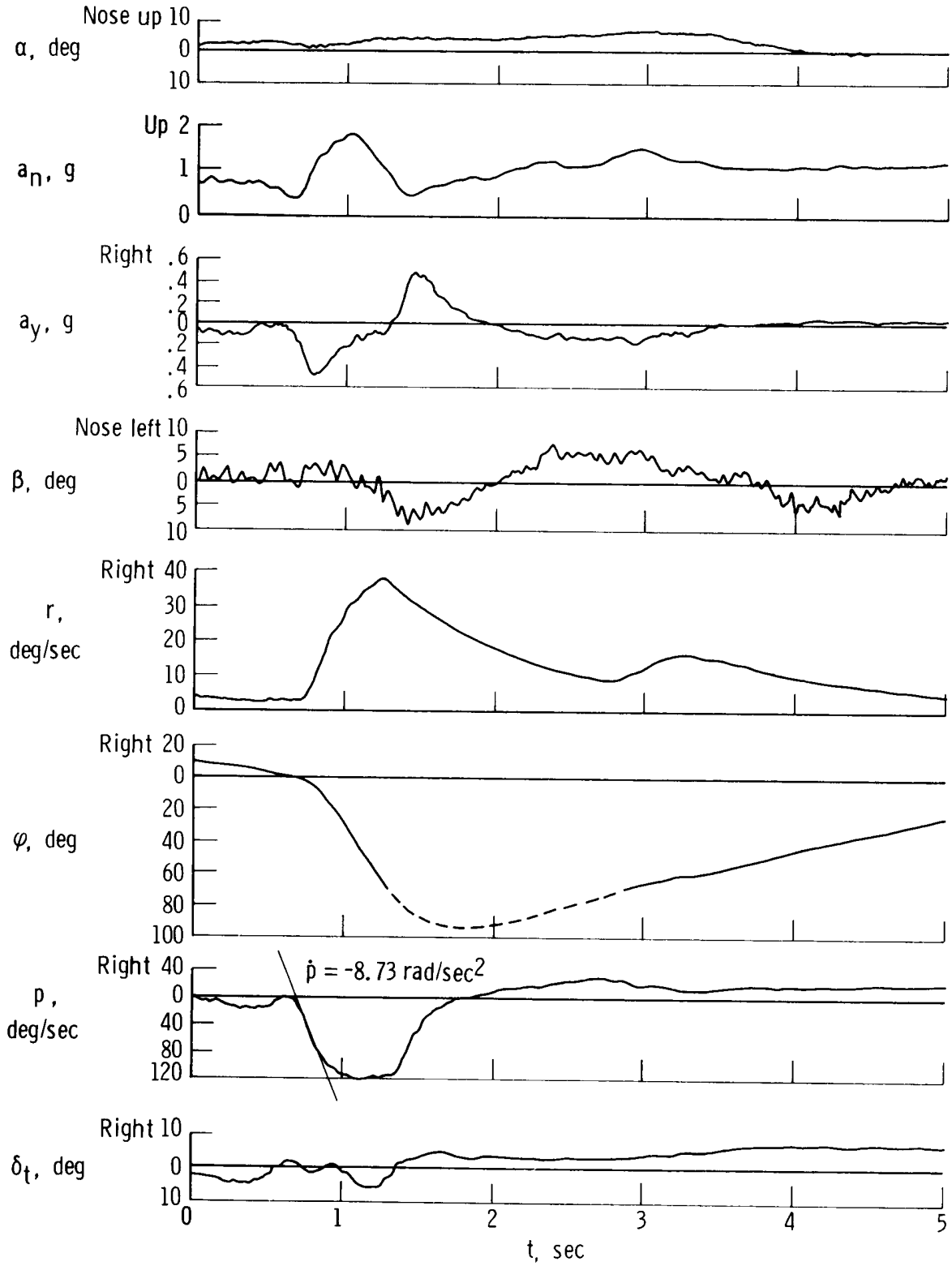
(a) F-104, probe airplane; C-5A, generating airplane; separation distance = 16.5 km (8.9 n. mi.).

Figure 2. Time history of five probe airplane responses to the C-5A and Convair 990 vortex wakes.



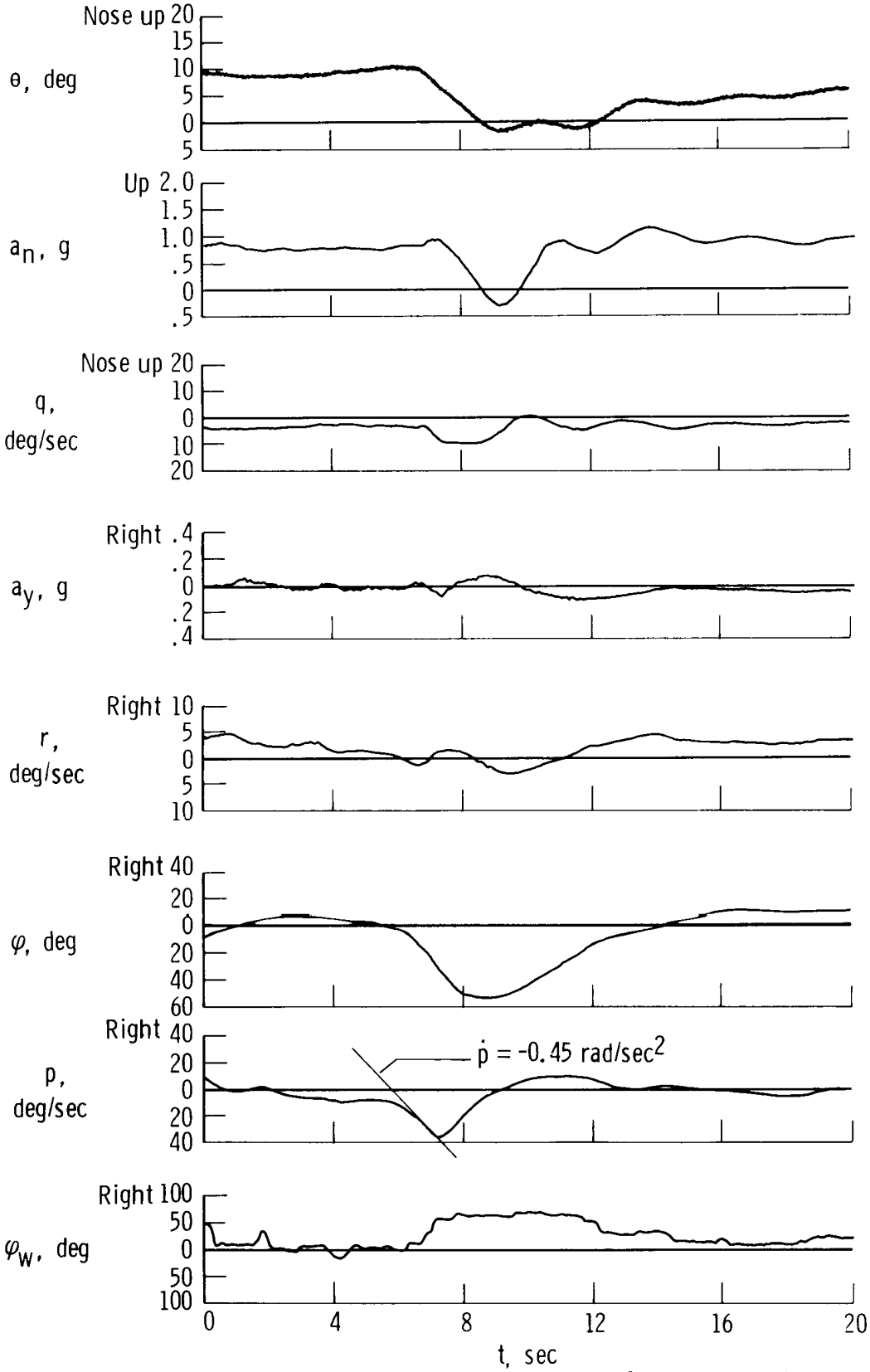
(b) Learjet 23, probe airplane; C-5A, generating airplane; separation distance = 6.85 km (3.7 n. mi.).

Figure 2. Continued.



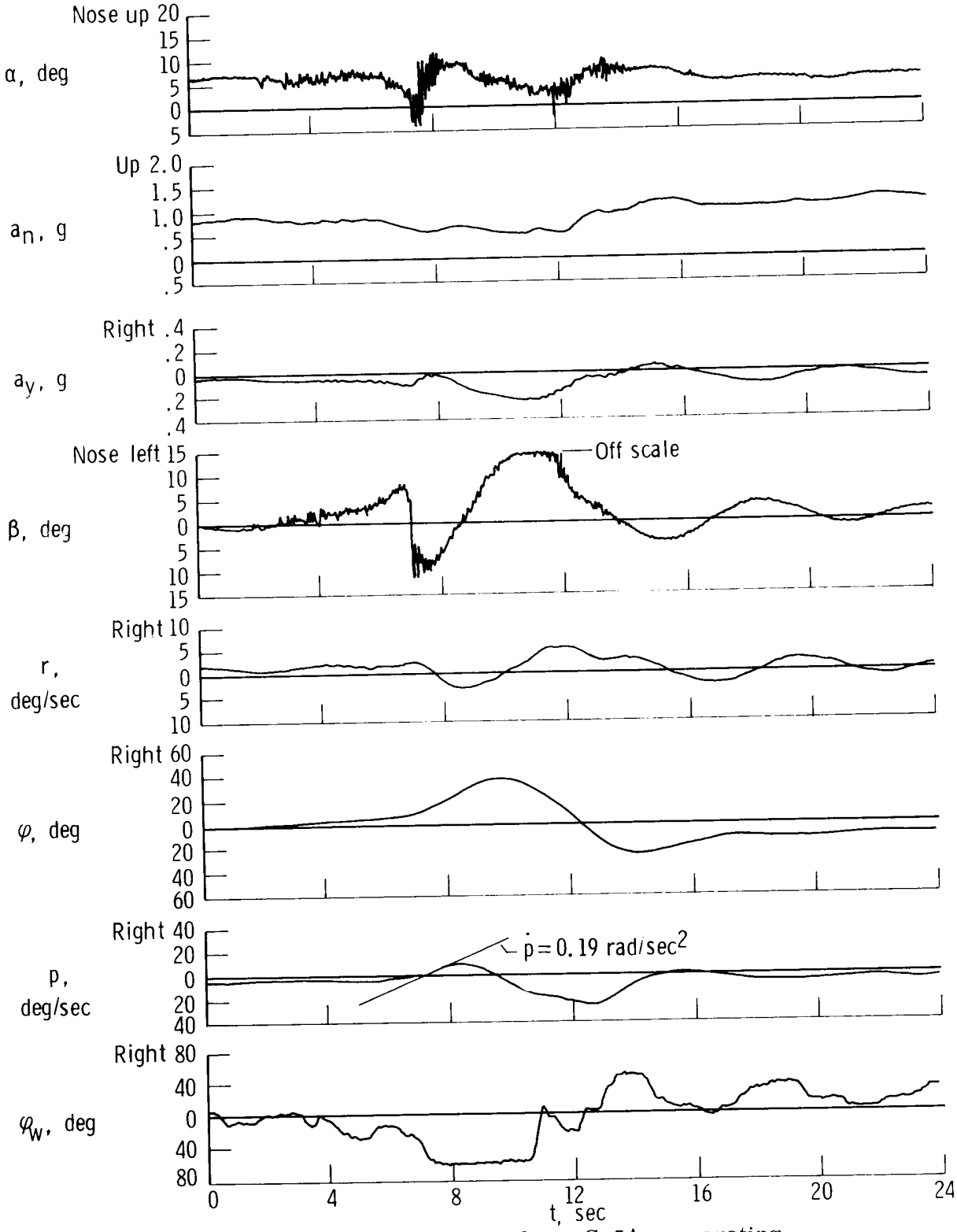
(c) Cessna 210, probe airplane; Convair 990, generating airplane; separation distance = 5.18 km (2.8 n. mi.).

Figure 2. Continued.



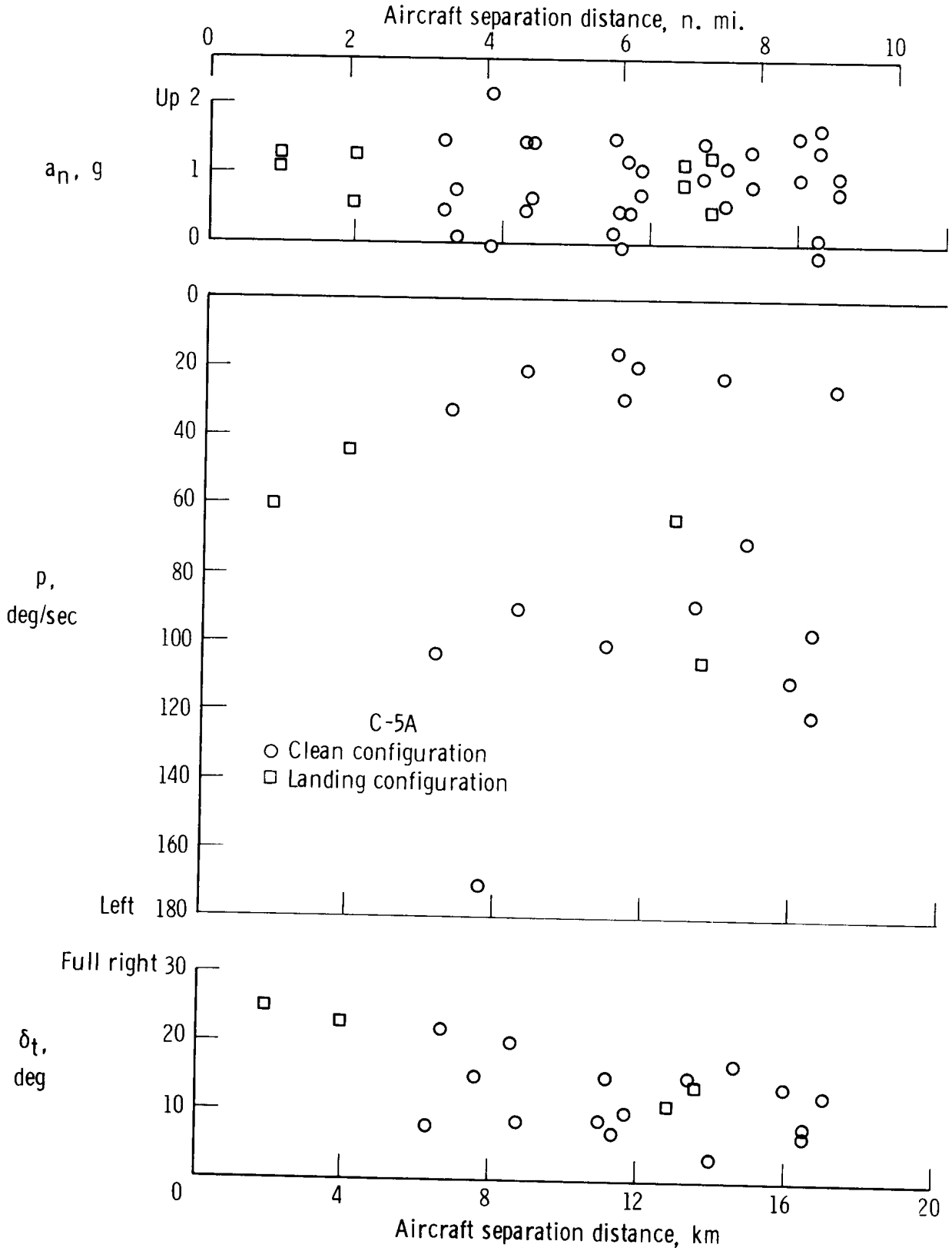
(d) DC-9, probe airplane; C-5A, generating airplane; separation distance = 8.7 km (4.7 n. mi.).

Figure 2. Continued.



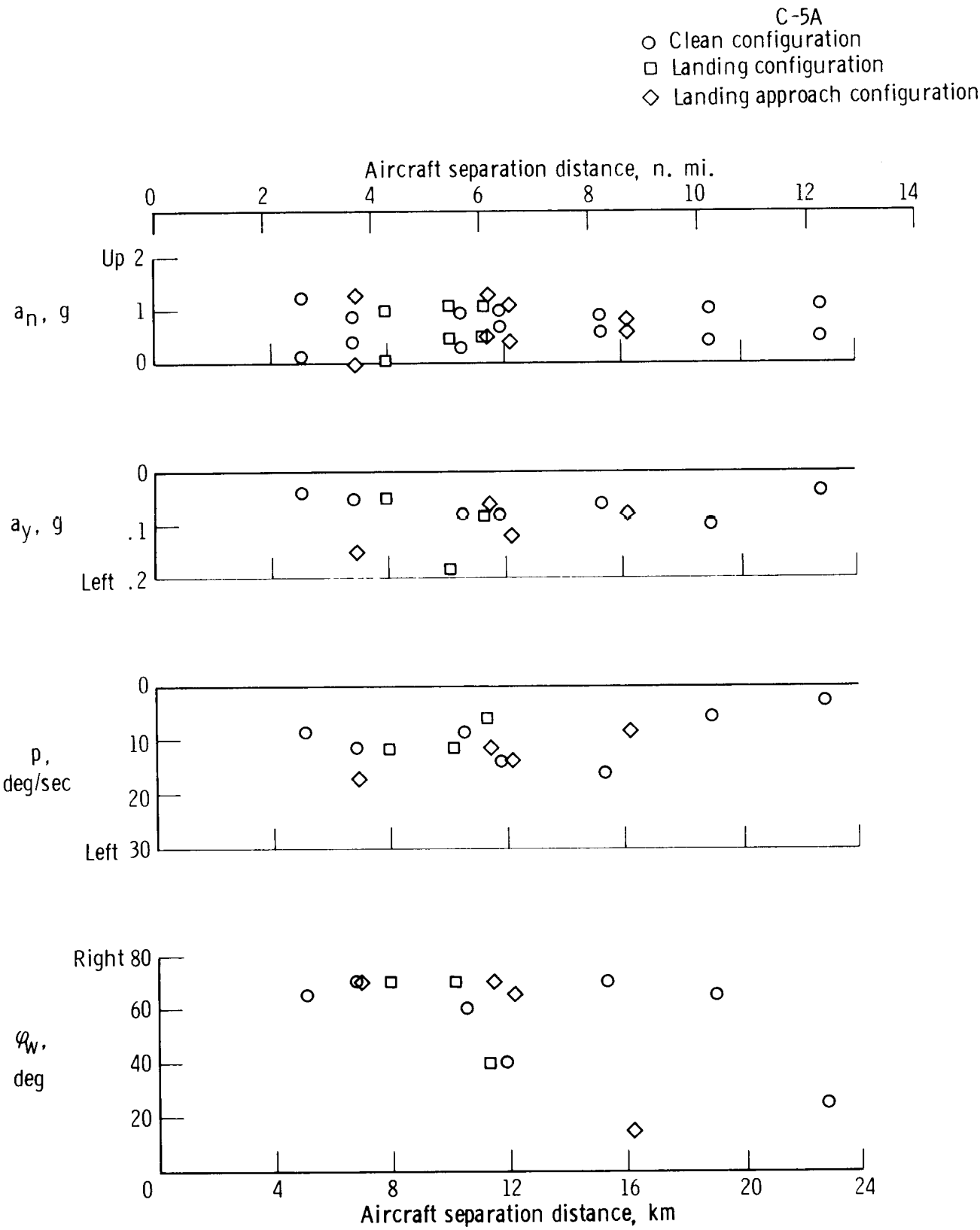
(e) Convair 990, probe airplane; C-5A, generating airplane; separation distance = 5.37 km (2.9 n. mi.).

Figure 2. Concluded.

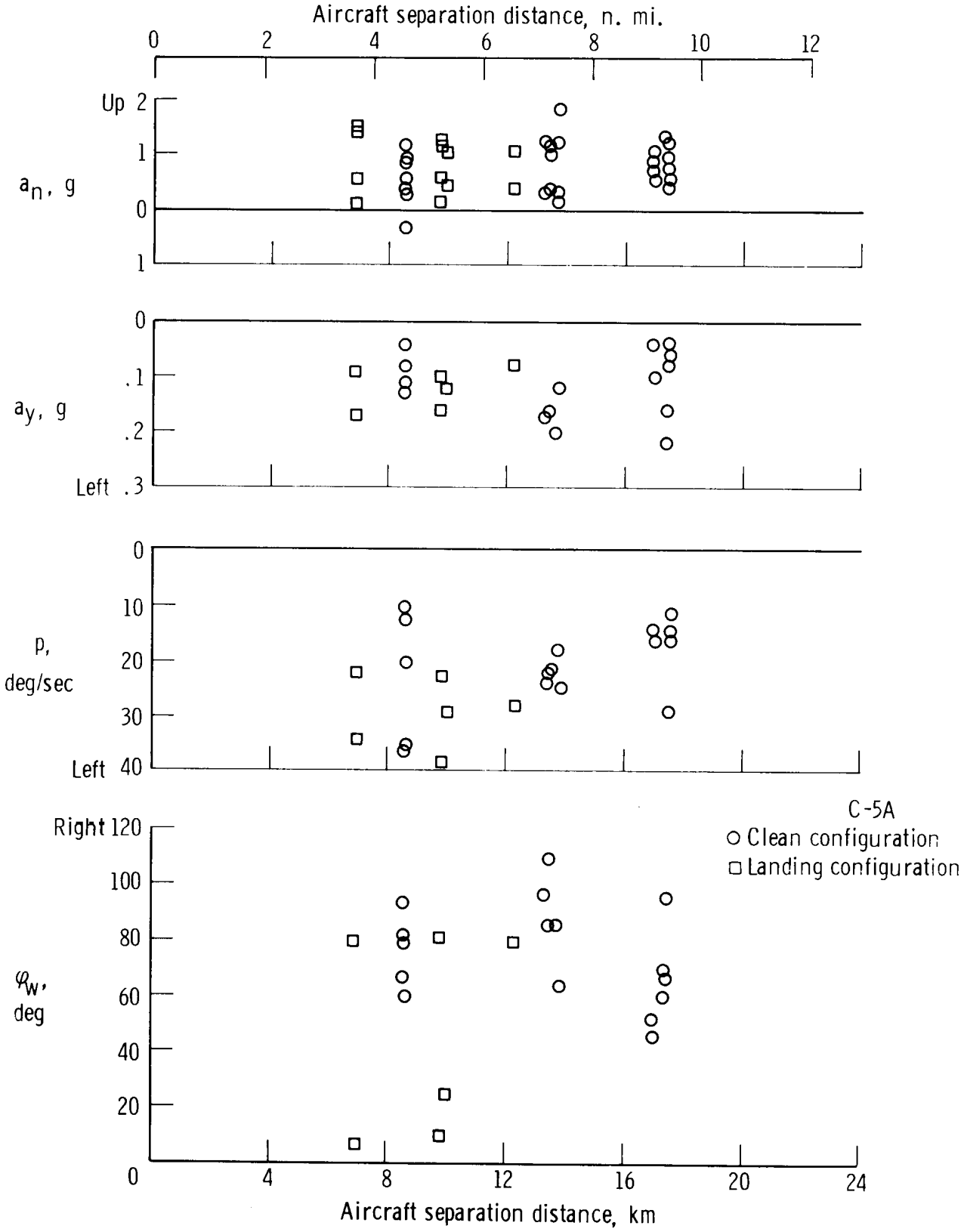


(a) F-104.

Figure 3. Maximum responses and lateral control inputs of five probe airplanes intersecting the C-5A vortex wake.

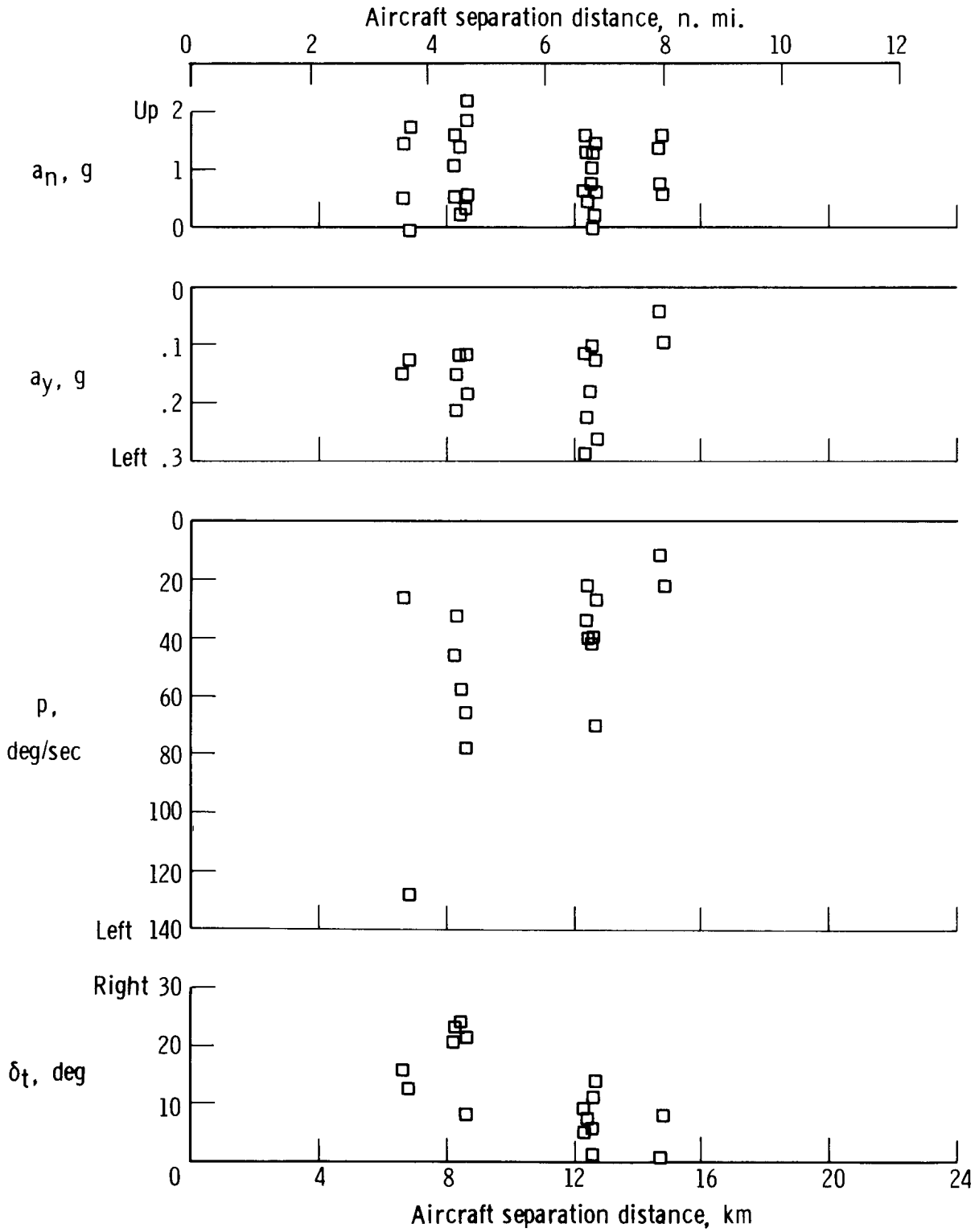


(b) Convair 990.
Figure 3. Continued.



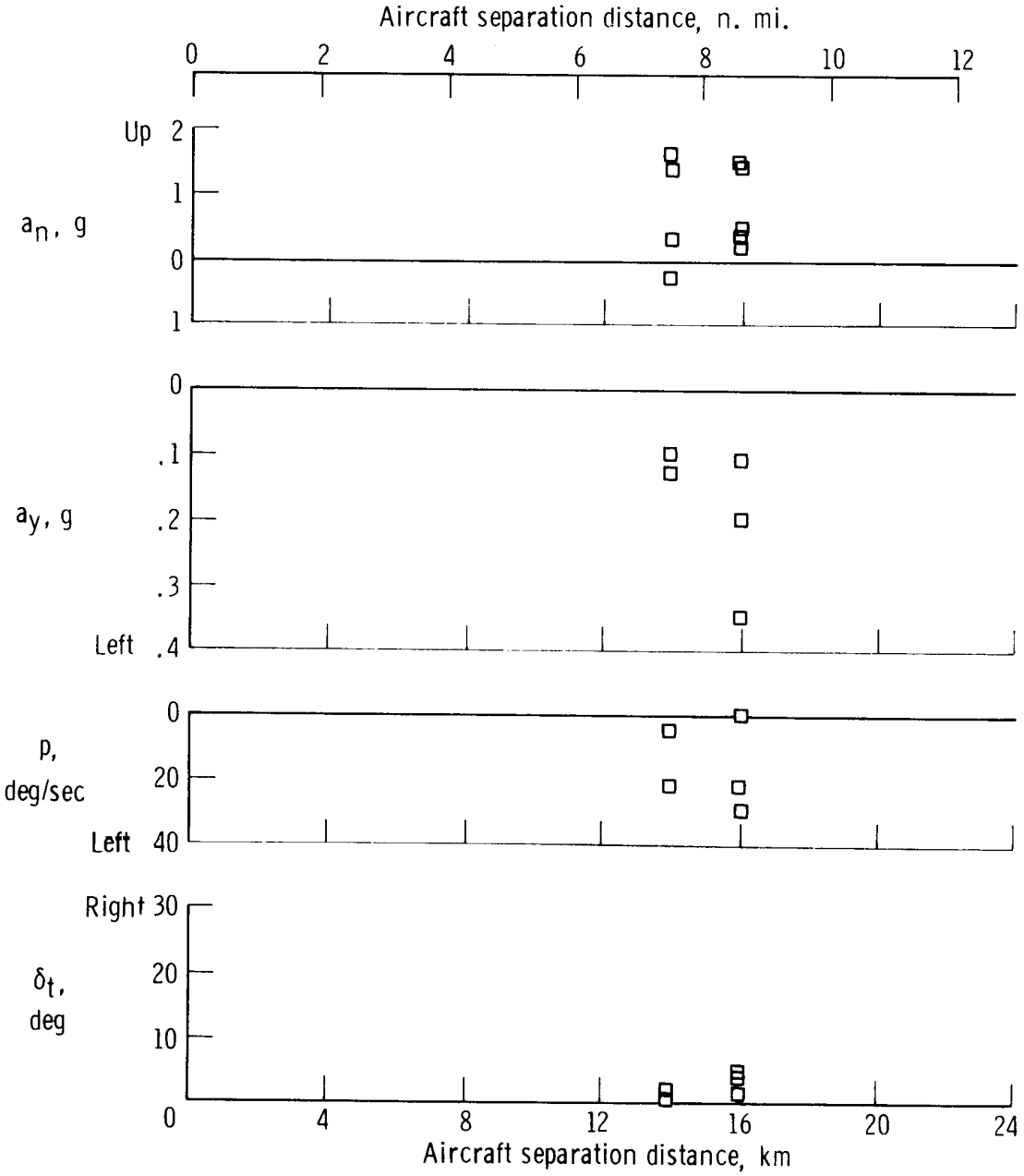
(c) DC-9.

Figure 3. Continued.



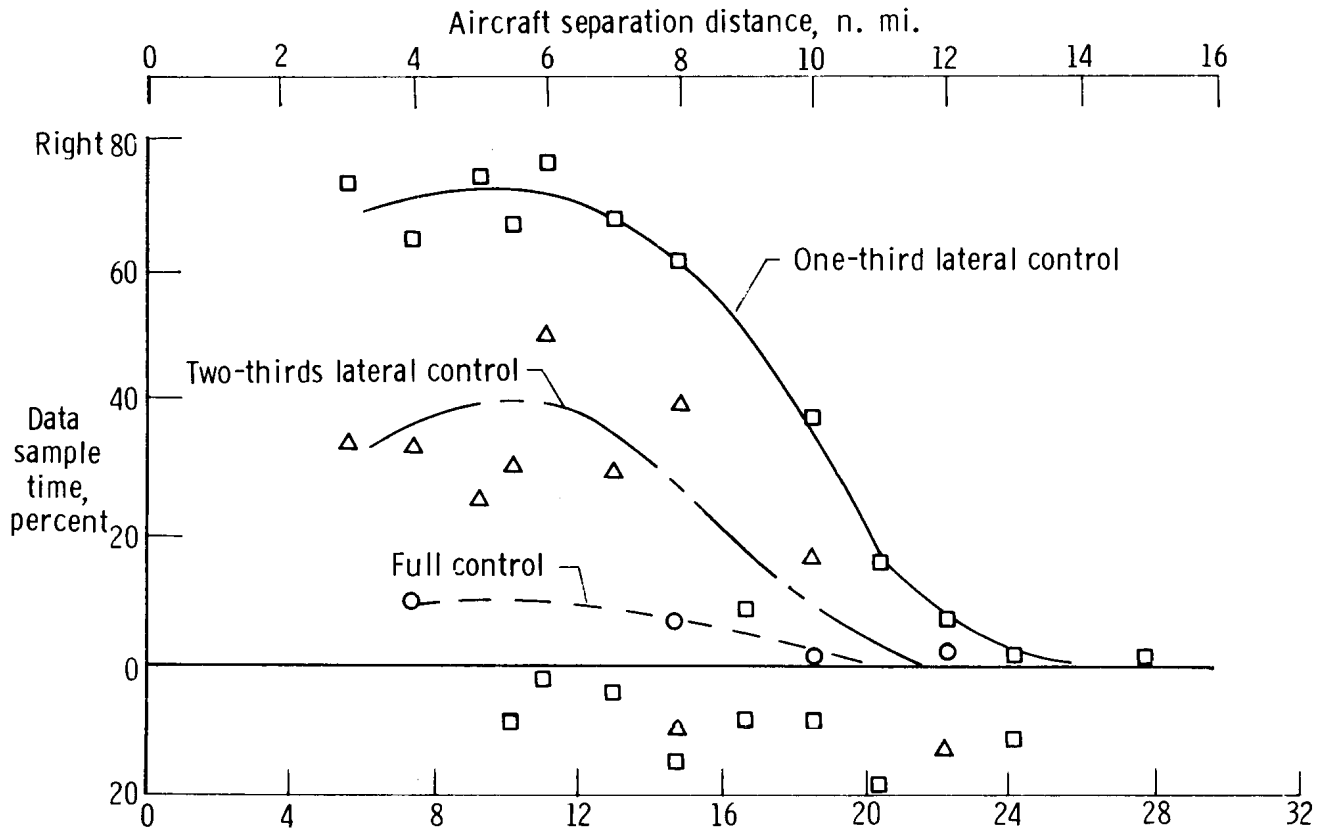
(d) Learjet 23 (C-5A landing approach configuration).

Figure 3. Continued.

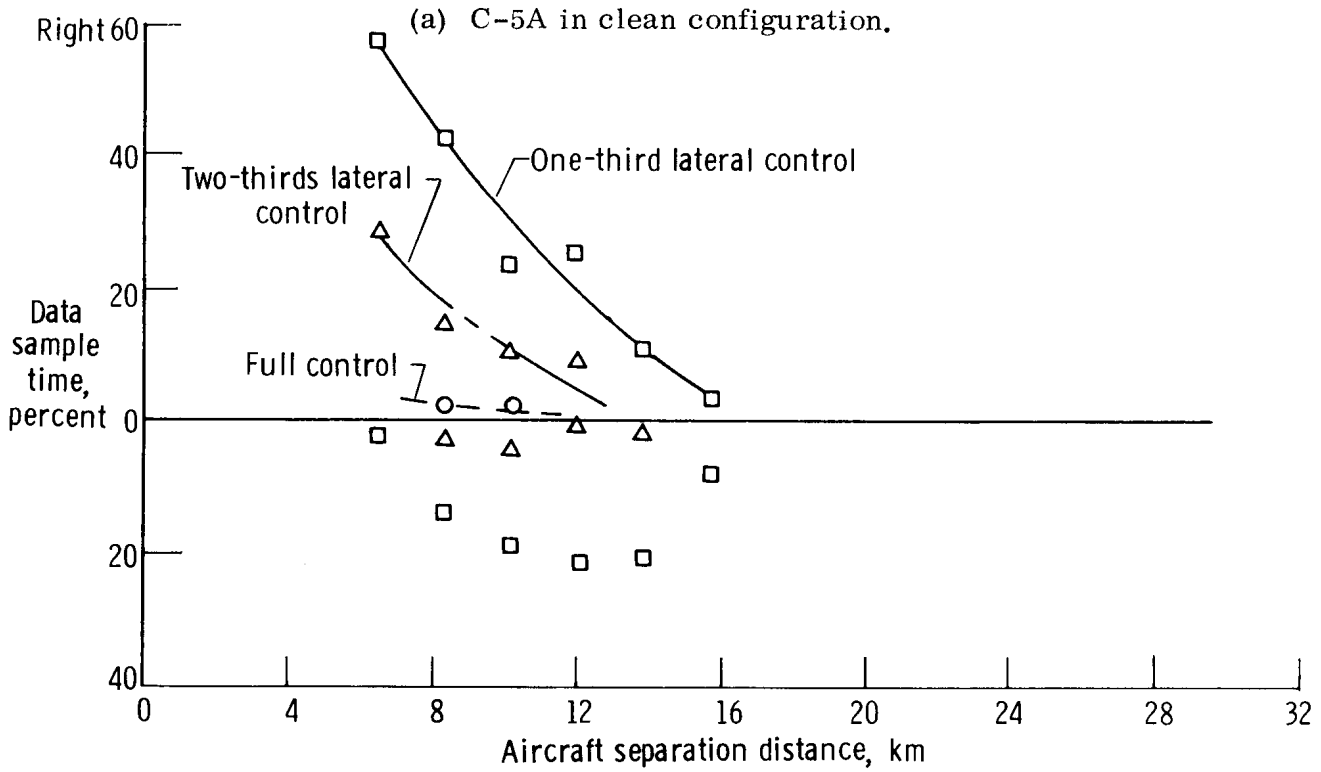


(e) Cessna 210 (C-5A landing approach configuration).

Figure 3. Concluded.

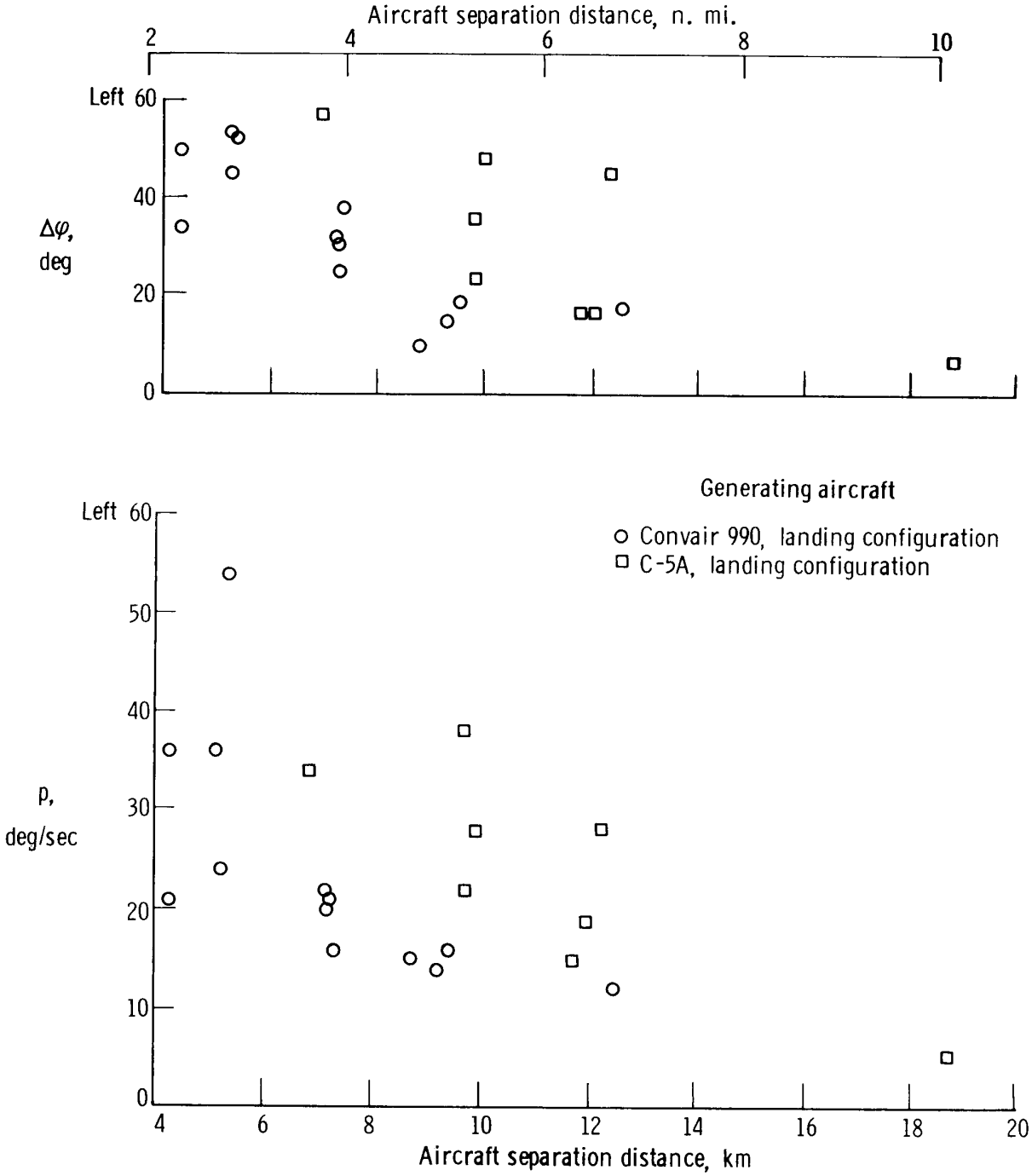


(a) C-5A in clean configuration.



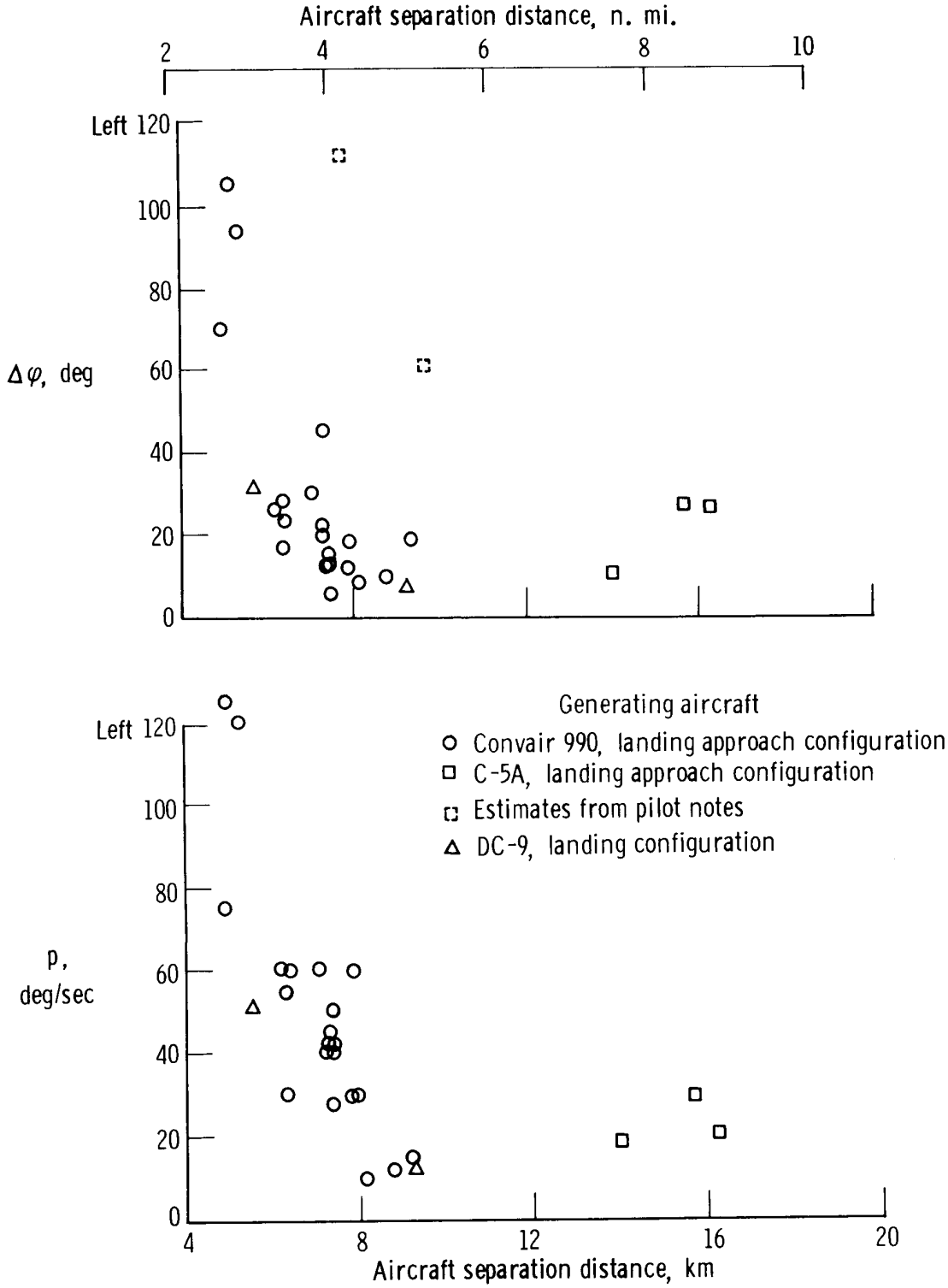
(b) C-5A in landing configuration.

Figure 4. Convair 990 lateral control effort required when flying in the C-5A vortex wake.



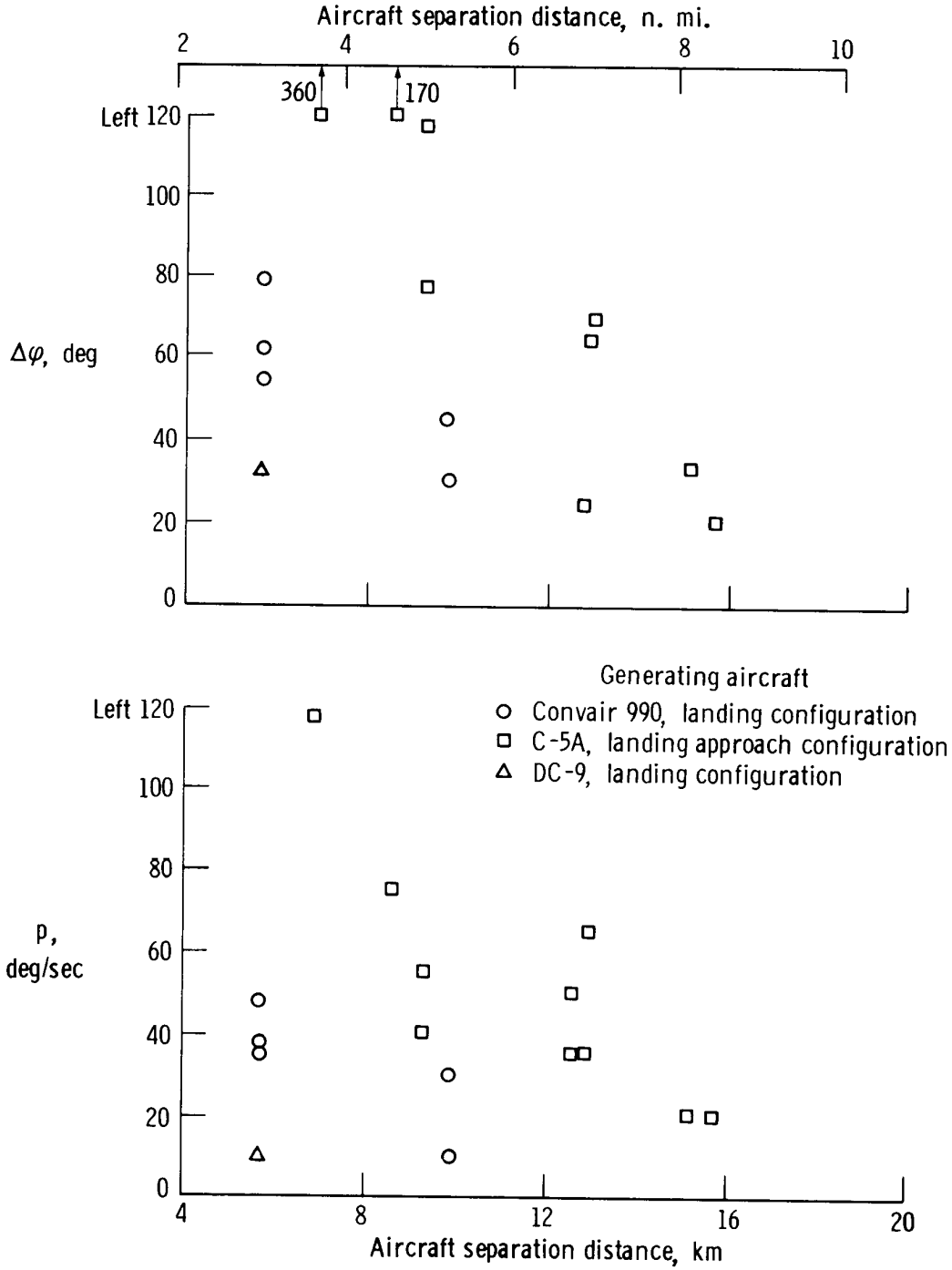
(a) DC-9 (landing configuration).

Figure 5. Comparison of maximum roll responses of various probe airplanes to the vortex wake of the DC-9, Convair 990, and C-5A aircraft.



(b) Cessna 210 (clean configuration).

Figure 5. Continued.



(c) Learjet 23 (landing approach configuration).

Figure 5. Concluded.

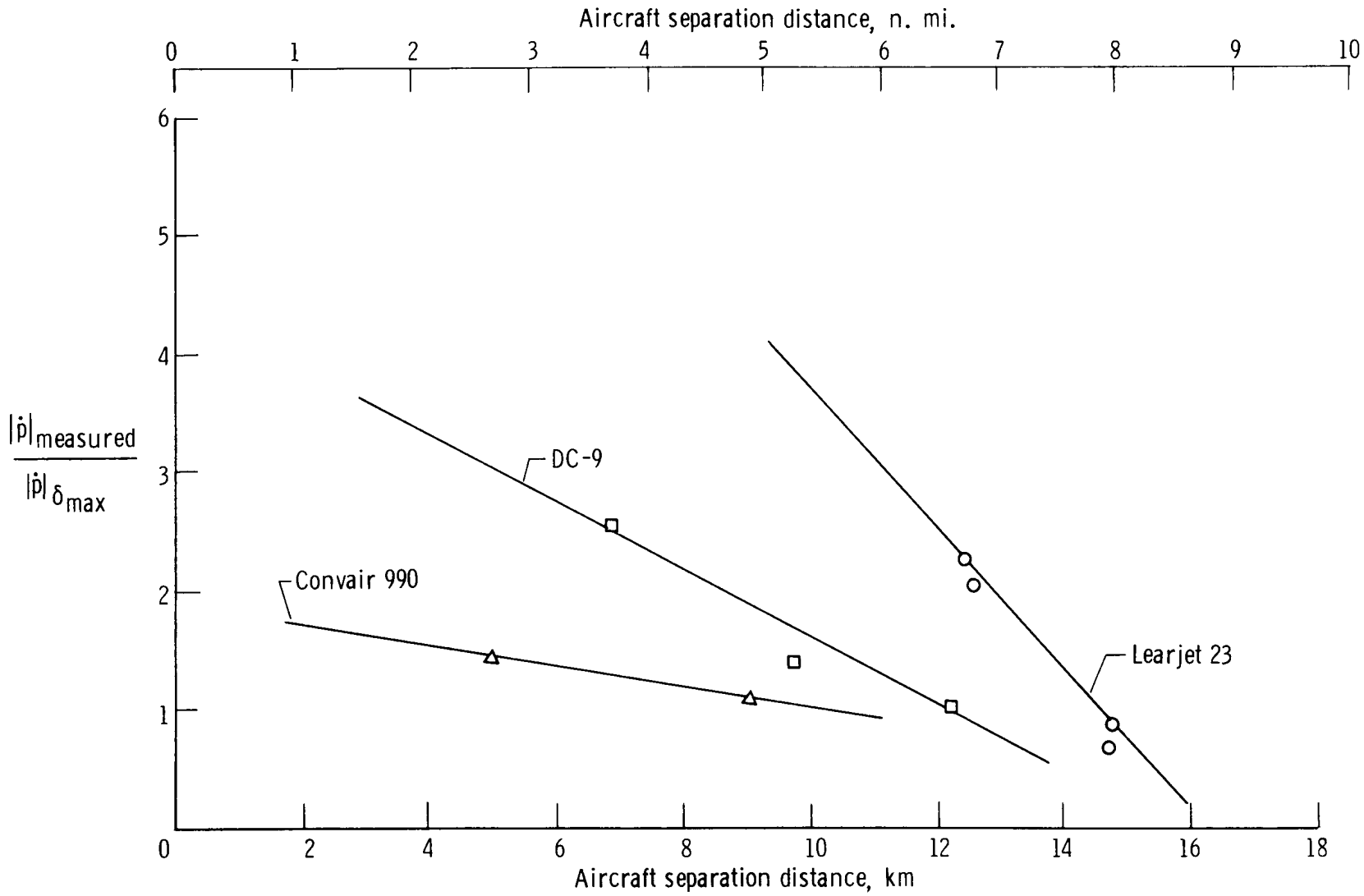


Figure 6. Ratio of vortex-induced roll acceleration to maximum lateral control power versus aircraft separation distance. Generating aircraft, C-5A; landing configuration; indicated airspeed, 150 knots.

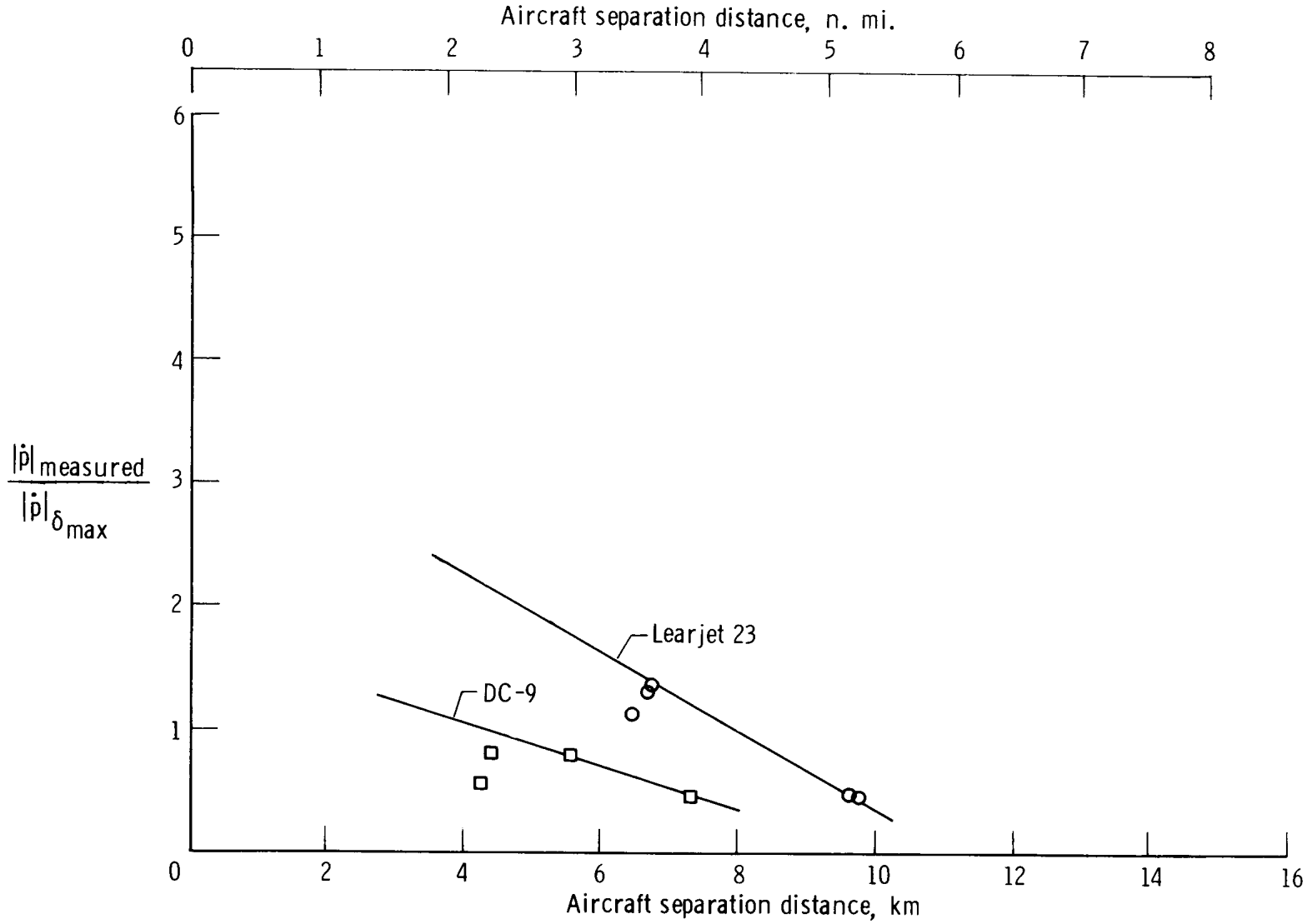


Figure 7. Ratio of vortex-induced roll acceleration to maximum lateral control power versus aircraft separation distance. Generating aircraft, Convair 990; landing configuration; indicated airspeed, 150 knots.

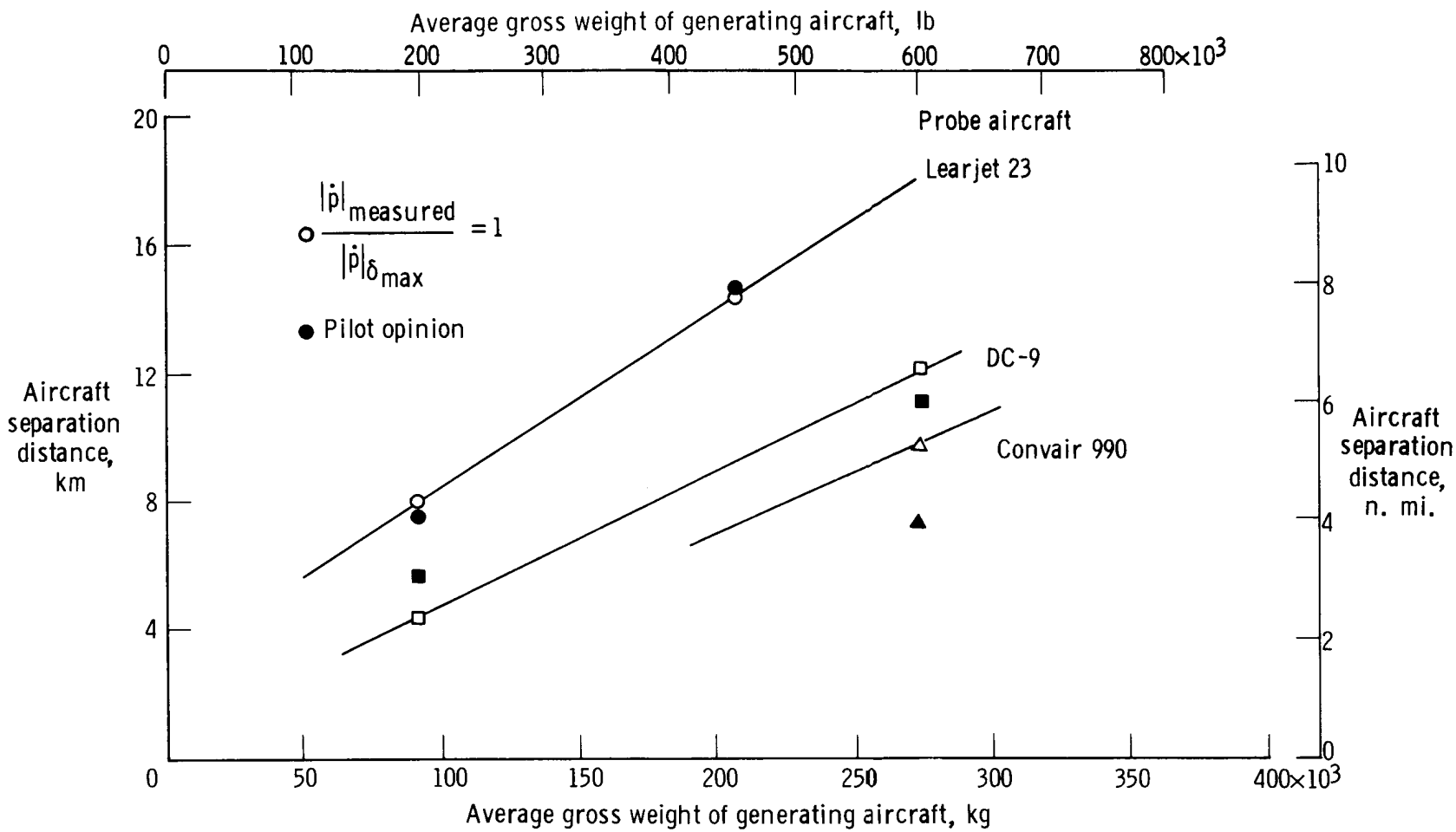


Figure 8. Comparison of pilot opinion with the suggested method for determining minimum separation.